NASA'S ADVANCED CRYOCOOLER TECHNOLOGY DEVELOPMENT PROGRAM (ACTDP)

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ABSTRACT

Over the years, NASA has developed a wide variety of new cryocooler technologies, as they represent a significant enabling capability for both Earth and space-science missions. Recent achievements include 50-80 K Stirling, pulse tube, and Brayton flight cryocoolers, and multistage development-model coolers at temperatures down to 10 K. The largest technology push within NASA right now is in the temperature range of 4 to 6 K. Missions such as the James Web Space Telescope, Terrestrial Planet Finder, and future generations of space telescopes, plan to use infrared detectors operating between 4 and 6 K. Similarly, future x-ray and microwave missions plan to use microcalorimeters and bolometers operating at milli-Kelvin temperatures and will require 4-6 K cooling to precool their sub-Kelvin refrigerators. To address cryocooler development for these next-generation missions, NASA initiated the Advanced Cryocooler Technology Development Program (ACTDP) in 2001. Since that time, the program has completed detailed designs and development-model hardware of three hybrid pulse tube and Stirling cryocooler concepts for cooling to 4-18 K. This paper presents an overview of the ACTDP program including programmatic objectives and timelines, and summarizes the excellent progress of the three design concepts being fabricated and tested at this time.

KEYWORDS: Cryocoolers, JWST, TPF, Con-X, ACTDP, MIRI, 6 K, Joule Thomson
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INTRODUCTION

NASA programs in Earth and space science observe a wide range of phenomena, from atmospheric physics and chemistry to stellar birth. Many of the instruments require low-temperature refrigeration to enable use of cryogenic detector technologies to improve dynamic range, or to extend wavelength coverage. Over the last four decades, NASA, often in collaboration with the US Air Force, has funded cryocooler technology development in support of a number of missions [1,2]. The largest utilization of coolers is currently in Earth Science instruments operating at medium to high cryogenic temperatures (50 to 80 K); this reflects the relative maturity of the cryocooler technology at these temperatures.

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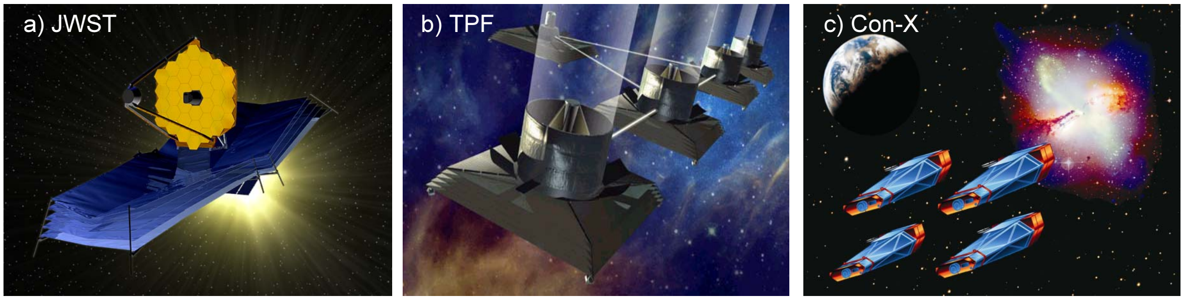

FIGURE 1. Artist's illustration of the: a) James Webb Space Telescope, b) TPF formation-flying interferometer, and c) Constellation-X.

For the future, NASA, in conjunction with our world partners, is planning ever more capable space observatories to extend the science discoveries that have been achieved to date. To address cryocooler developments meeting these challenges, NASA initiated a program referred to as the Advanced Cryocooler Technology Development Program (ACTDP) in 2001 [3]. This development program has made excellent progress in providing cryogen-free multi-year cooling for low-noise detector systems at temperatures of 6 K and below.

Before reviewing this excellent technical progress, we first step back and summarize the overall ACTDP program focus, objectives, and timelines.

ACTDP PROGRAM FOCUS

To provide detailed requirements for prototype ACTDP refrigerators, three future observatory missions that need 6 K cooler technology were identified as the ACTDP core missions in summer 2001. These observatories span the electromagnetic spectrum from the far infrared to X-rays and include the infrared-viewing James Webb Space Telescope (JWST), the Terrestrial Planet Finder (TPF) interferometer mission, and the Constellation-X (Con-X) X-ray mission. All three missions, illustrated in FIGURE 1, were identified as having similar requirements for cooling near 6 K, as benefiting from secondary cooling near 18 K, and as having similar orbital thermal environments. An important part of the ACTDP program was carefully examining each of these missions to insure that the developed technologies fulfilled the mission's needs. Prior to describing additional details of the ACTDP program it is useful to briefly review the features of each of these three missions.

James Webb Space Telescope

Chosen to replace the Hubble Space Telescope (HST), which was first launched in 1990, JWST is designed to examine the Universe in wavelengths between 0.6 and 28 microns during a mission lasting up to ten years. Unlike HST, which is in a Shuttle-accessible low-Earth orbit, JWST will be located in deep space in an Earth-tracking L2 orbit. At this location, a fixed 1.5 million km from Earth, JWST’s huge 6½-meter telescope (FIGURE 1a) will be passively cooled to 30−50 K. Another implication of this orbital location is that periodic repair and refurbishment, as was successfully used many times with HST, will not be possible with JWST. Thus, refrigerator reliability and long life will be particularly important. A second attribute of the JWST configuration is the need to locate the cryogenic telescope several meters away from the room-temperature spacecraft bus. This constrains the room-temperature refrigerator compressors to be located remote from their 6 K and 18 K cold heads. Although the requirements for low vibration and EMI are not as demanding as with HST due to JWST's vibration isolation between the spacecraft and telescope, they are still very important for the JWST coolers. In the area of cooling temperatures, JWST's Mid InfraRed Instrument (MIRI), the lowest temperature instrument on JWST, uses low-noise arsenic-doped silicon detectors that require operation at 7 K.

Terrestrial Planet Finder

The TPF mission objective is searching for earth-like planets around nearby stars, providing the first direct imaging of such planets, and performing low resolution spectroscopic studies of the planetary atmospheres. To meet these objectives, two TPF system architecture concepts are under study: visible coronagraphs, and infrared nulling interferometers. A formation-flying version of a TPF nulling infrared interferometer is illustrated in FIGURE 1b. It would involve infrared sensors at temperatures similar to those on JWST, and like JWST, the optics on each spacecraft would have a multilayer thermal shield to provide passive cooling to 30–50 K. With this concept, the spacecrafts are positioned normal to the direction of observation and relay the starlight to a beam combiner. The starlight is rejected in the nulling beam combiner, and the planet light is sent through to a spectrometer.

For such a interferometric system, observing in the infrared from ~5-20 microns, cooling the detectors to around 6 K is required over a mission lifetime of 5 to 10 years. Also, as was done on JWST, room-temperature and vibration-prone refrigerator compressors will have to be located on the main spacecraft bus, possibly meters away from the cold and vibration-stabilized optics and detector module.

Constellation-X

The Constellation-X mission complements the previous two NASA missions by working in a different wavelength region of the electromagnetic spectrum—X-rays. It supports NASA's exploration of the structure and evolution of the universe theme by focusing on unlocking the mysteries of black holes, galaxy formation, and the still undetected matter in the Universe. It consists of a group of four spacecraft, conceptually shown in FIGURE 1c, each carrying two X-ray telescopes.

The key science detectors in Con-X's soft X-ray telescopes are microcalorimeters. These must be maintained at 50 mK to achieve the very high spectral resolution required from 0.3–10 keV. To cool the detectors, a multistage refrigeration system is envisioned, consisting of a 6 K/18 K ACTDP cryocooler to cool from room temperature down to 6 K, followed by a multistage magnetic refrigerator to cool from 6 K to 50 mK. Like NGST and TPF, the Con-X constellation will also be located in a remote L2 orbit. However, these X-ray telescopes lack the 30–50 K cold optics of the other two missions and therefore lack some of their compressor/cold head separation and deployment constraints.

ACTDP PROGRAMMATIC OVERVIEW

The Initial Study Phase

To develop the needed cryocooler technology for the above described missions, NASA initiated the ACTDP program in 2001 under the leadership of the Jet Propulsion Laboratory, and in collaboration with the NASA Goddard Space Flight Center. The effort started with the generation of detailed requirements and specifications in summer 2001, leading to a country-wide request for proposals in November 2001. This resulted in the award of four parallel study-phase contracts by April 2002 to the following vendors [3]:

- Ball Aerospace of Boulder, CO for a hybrid Stirling/Joule-Thomson cooler
- Creare, Inc. of Hanover, NH for a hybrid radiator/turbo-Brayton cooler
- Lockheed Martin ATC of Palo Alto for a 4-stage pulse tube cryocooler
- TRW of Redondo Beach, CA for a hybrid pulse tube/Joule-Thomson cooler

With the 35-page cryocooler requirements specification providing guidance, each contractor developed a detailed preliminary design with supporting laboratory test data sufficient to confidently enter into the hardware development and demonstration phase. The study phase culminated with a Preliminary Design Review (PDR) in September 2002, with the proposed

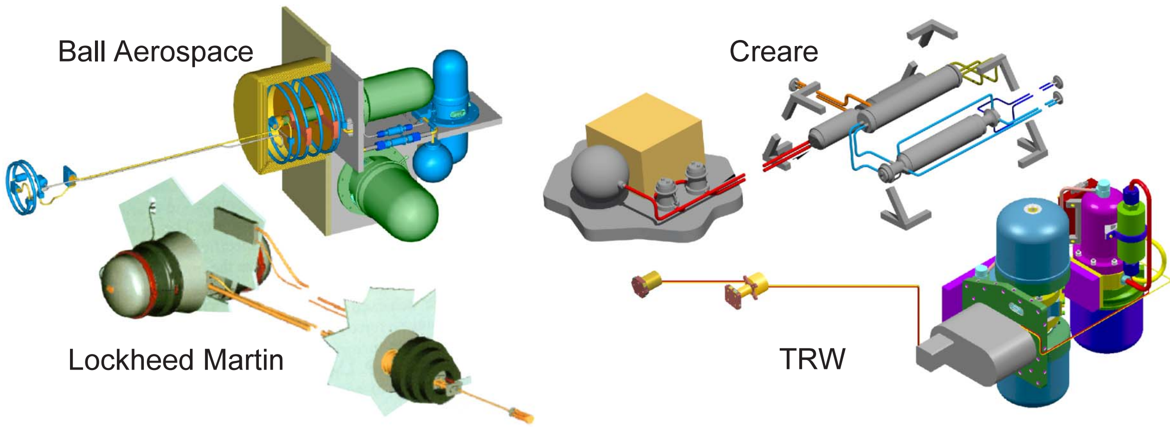

FIGURE 2. The four ACTDP study-phase cryocooler concepts.

coolers documented in study-phase final reports and proposals for the Demonstration Phase. FIGURE 2 provides a pictorial overview of the four study-phase coolers.

ACTDP Demonstration Phase

Based on the Study-Phase results and Demonstration-Phase proposals, three of the ACTDP cryocooler concepts (Ball, TRW and Lockheed) were selected to progress into the demonstration phase. Each was thoroughly integrated into the three core mission concepts (JWST, TPF and Con-X) to confirm that the cooler designs met the system requirements. JWST, in particular, was closely examining the possible use of an ACTDP cooler to cool the MIRI instrument, and led a detailed 6-month accommodation study starting in November 2002 to quantify the cryocooler's performance in comparison to a solid hydrogen cryostat [4]. Although the solid hydrogen cryostat was selected in favor of an ACTDP cryocooler at that time, the JWST cryocooler study was extremely valuable in allowing the performance and integration capabilities of the ACTDP cryocooler concepts to be understood and refined based on the in-depth examination of an actual flight application.

Using the results of these mission accommodation studies, the ACTDP specifications were upgraded in April 2003, particularly in the areas of cooldown load versus temperature and overall cooling load distribution between the 6 K and 18 K stages. Whereas the original ACTDP specification of 2001 was for 7.5 mW at 6 K plus 250 mW at 18 K, the latest load requirements were revised to 30 mW at 6 K plus 150 mW at 18 K. These upgraded specifications, one for each of the three design concepts, provided the focus for re-tailoring the ACTDP preliminary designs in preparation for delta Preliminary Design Reviews (ΔPDRs) that were conducted prior to initiating the detailed designs of the coolers (see FIGURE 3).

Work on the detailed designs commenced in the Fall of 2003 striving toward Engineering Model (EM) mechanical cryocoolers that were fully flight-like in form, fit, and function. It was important that the fabricated hardware allow assessment of the cooler's ability to meet all key thermal, structural, and reliability/lifetime performance requirements. The cryocoolers also needed to be capable of providing the required cooling system performance over the full range of interface temperatures, and be suitable for multi-year life-testing, including assessment of susceptibility to internal or external gaseous contamination over time.

In Spring 2004, synchronous with funding reductions and programmatic delays of the three NASA core missions, the ACTDP effort was also rescoped and stretched an additional year, providing increased time for a greater level of technology development during the engineering and breadboard-testing phase of the effort. Consistent with this increased technology development focus, the ACTDP hardware deliverable coolers were also redefined as Development Models (DM) to allow inclusion of more testbed features and instrumentation, and less flight-cooler rigor in areas of low development risk.

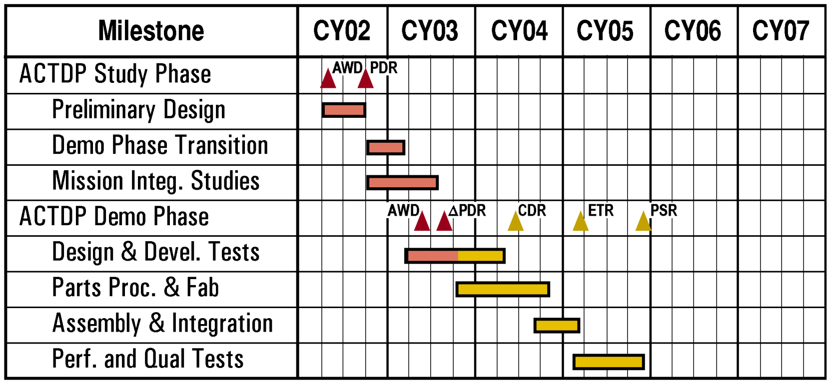

FIGURE 3. Original ACTDP development schedule showing the planned phases of the effort.

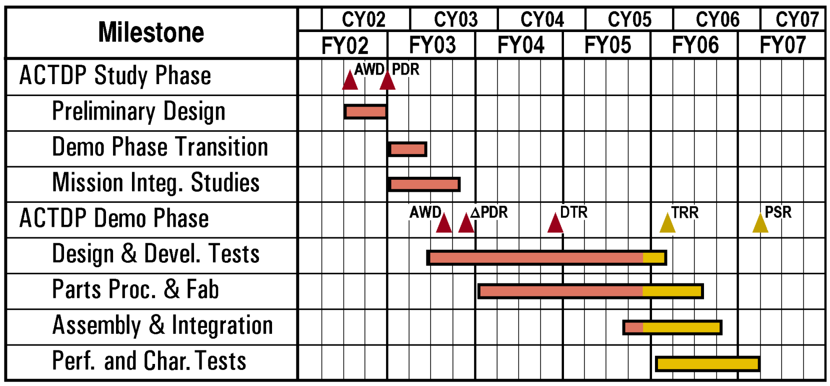

FIGURE 4. ACTDP DM activities and milestones in response to updated 2004 NASA mission objectives (DTR – Development Test Review, TRR – Technology Readiness Review, PSR – Pre-Ship Review).

ACTDP DEVELOPMENT MODEL ACTIVITIES

The new ACTDP milestones, shown in FIGURE 4, were scheduled to systematically retire the key development risks prior to the end of 2006. In particular, the Development Test Reviews (DTR) held in September 2004 provided a completion gate for the key testbeds, and signaled the start of testing of the critical assemblies of each of the three concepts. This past year, the individual assembly designs were repeatedly refined and tested in preparation for the Technology Readiness Reviews (TRR) scheduled for Fall 2005.

In the most recent turn of events, a cryocooler accommodation study was conducted in March 2005 to see if significant mass could be saved by replacing the solid hydrogen dewar used to cool the Mid InfraRed Instrument (MIRI) on JWST with an ACTDP cryocooler. Based on this study, and after confirming that the cryocooler development risks were consistent with JWST's schedule, a decision was made to adopt an ACTDP cryocooler for cooling MIRI. This handoff to a flight program with a launch scheduled for the 2012 timeframe accomplishes the fundamental objective of the ACTDP program. Also, with this transfer, the TRRs scheduled for Fall 2005 are expected to coincide with the selection of the contractor for the MIRI flight cryocoolers.

The progress of each of the three ACTDP cryocooler concepts is summarized below:

Ball Aerospace Hybrid Stirling/JT

Ball Aerospace's ACTDP cryocooler concept [5] utilizes a multi-stage Stirling refrigerator to precool a Joule-Thomson (JT) loop powered by an Oxford-style compressor with reed valves. The JT loop provides remote cooling of both 6 K and 18 K loads, thus allowing the loads to be isolated from compressor-generated vibration and EMI. The multi-stage refrigerator is based on leveraging existing Ball Stirling coolers, JT coldend technology, and drive electronics.

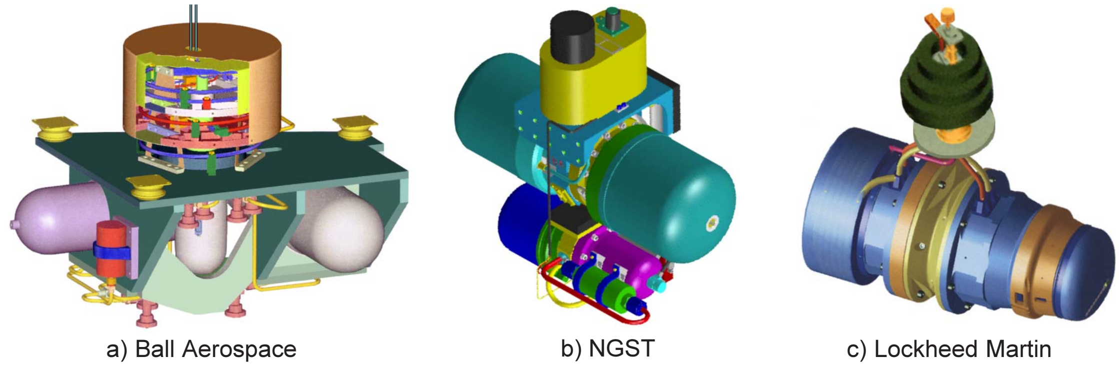

FIGURE 5. The three ACTDP development-phase cryocooler concepts.

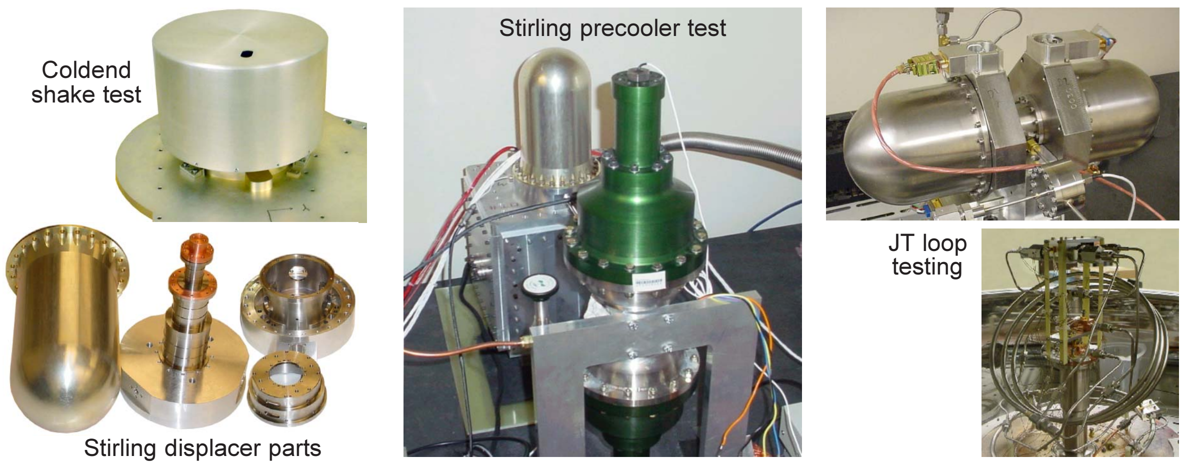

FIGURE 6. Ball ACTDP cryocooler breadboard and testbed technologies.

During the ACTDP development phase, optimization of the Ball concept led to the revised configuration shown in FIGURE 5a, and plans for focused technology development on the JT compressor and recuperators, and on the Stirling precooler, particularly the 3-stage Stirling displacer. FIGURE 6 illustrates some of the hardware elements used in these tests, including the integral back-to-back Oxford-style JT compressor with reed valves, the recuperators, and the new 3-stage Stirling displacer. Detailed designs were also generated for the overall integration of the JT components onto the precooler displacer to accurately assess the thermal parasitic loads and structural viability of this important part of the design. Launch vibration tests confirmed the coldend design's structural integrity.

During the JT-loop tests Ball demonstrated the performance of the entire 6 K JT flow loop. And, in Stirling precooler tests, they met their 250 mW at 15 K load target for the Stirling displacer. Details of Ball Aerospace's recent ACTDP development accomplishments are provided in a companion paper [6].

NGST Hybrid Pulse Tube/JT

Together with the other changes in 2003, TRW was acquired by Northrop Grumman and its name was changed to Northrop Grumman Space Technology (NGST). The NGST and Ball Aerospace ACTDP cryocooler concepts are similar in operation, but the NGST version utilizes a multi-stage pulse tube (PT) cryocooler to precool the JT loop instead of a Stirling cooler. Powered by a linear-motion Oxford-style compressor with reed valves, the JT loop provides remote cooling of both 6 K and 18 K loads, thus allowing the loads to be isolated from any compressor-generated vibration and EMI. During the ACTDP development phase, optimization of the NGST concept led to the configuration shown in FIGURE 5b [7]. This unit is based on leveraging existing NGST flight-quality pulse tube compressors and drive electronics; in

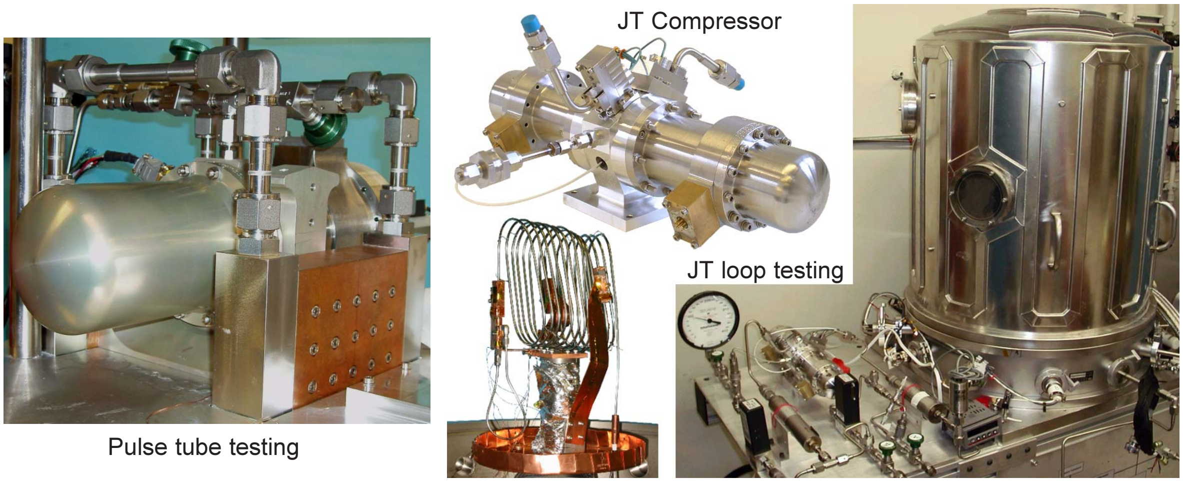

FIGURE 7. NGST ACTDP cryocooler pulse tube and JT loop development testing.

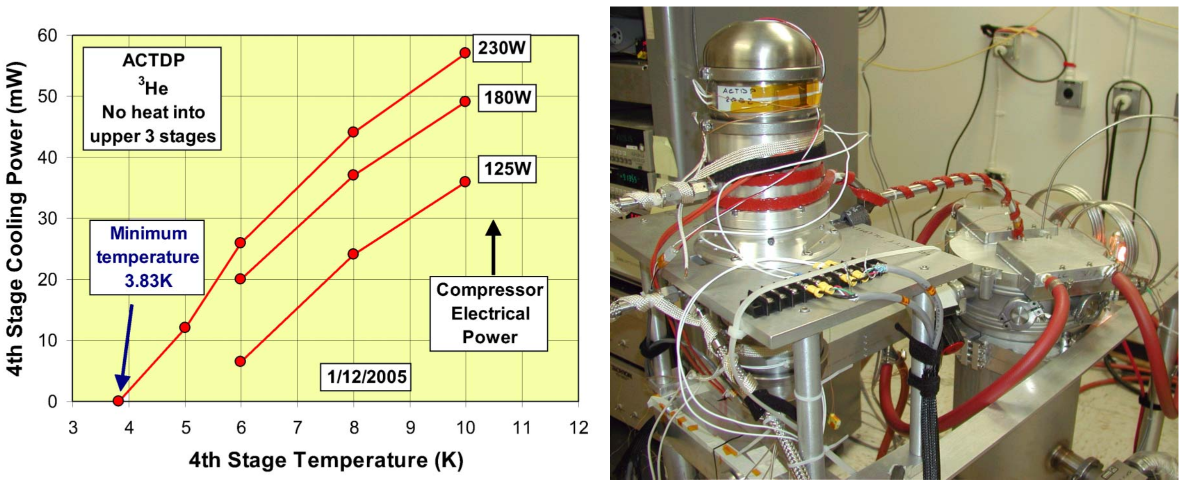

FIGURE 8. Lockheed Martin ACTDP DM cryoooler in system test.

particular, the precooler compressor is based on NGST's existing HCC PT compressor [8], and the JT compressor is their HEC PT compressor [9] with added reed valves.

FIGURE 7 illustrates some of the hardware elements used in their development tests including the new HEC-based JT compressor, the recuperators, and the 3-stage breadboard pulse tube precooler. Detailed designs are underway for the integration of the JT components onto the pulse tube precooler to verify the thermal parasitic loads and structural viability of this important part of the design. During JT loop tests with their new JT compressor, NGST has demonstrated the performance of the entire 6 K JT flow loop. In pulse tube precooler tests, they have demonstrated 250 mW of cooling at 15 K, at 50% maximum input power (75% maximum stroke) and the MIRI derived requirement of 160 mW at 18.5 K, at 25% maximum input power (50% maximum stroke). Details of NGST's recent ACTDP accomplishments are summarized in a companion paper [10].

Lockheed Martin ACTDP Cryocooler Concept

Lockheed Martin's ACTDP cryocooler concept utilizes a 4-stage pulse tube refrigerator, with an optional flow loop to cool remote 6 K loads. The single-unit multi-stage refrigerator leverages heritage Lockheed flight-quality pulse-tube compressors, cold heads, and drive electronics, and builds on laboratory pulse tube technology [11] that previously demonstrated direct cooling down to 4 K. During the ACTDP development phase, optimization of the Lockheed concept led to the configuration shown in FIGURE 5c. This unit is based on a refined compressor with increased efficiency and an all-new pulse tube expander [12].

FIGURE 8 shows the system-level test of the completed cryocooler and the excellent results achieved. Using ^{3}He as the working fluid, the refrigerator reached a no-load temperature of 3.83 K and provided 20 mW at 6 K together with 150 mW at 18 K for a compressor input power of 208 W. Details of the test results are provided in a companion paper [13].

SUMMARY

To enable a suite of ever more capable science observatories, NASA-funded technology development is now directed primarily at coolers in the 4-20 K temperature range. Initiated in 2001 with three future missions as its focus, the ACTDP ptogram has made significant progress in developing the needed long-life mechanical cryocoolers with the necessary cooling power and integration features to accommodate the 6 K/18 K cooling of its target missions. Three alternative concepts are under development: two hybrid systems using Stirling/Joule-Thomson and pulse tube/Joule-Thomson combinations, and a four-stage pulse tube with an optional integral flow loop. These are now nearing the end of their breadboard fabrication and development-test phase. Based on their excellent progress, in April 2005 the ACTDP coolers were selected to cool the MIRI instrument on JWST, and the ACTDP program was transferred to JWST to be managed as a flight cryocooler development program. This transfer to flight fulfills a fundamental objective of the original ACTDP program.

ACKNOWLEDGMENT

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